Ring Optics Issues

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On Behalf of the Beam Optics Group

The 28th KEKB Accelerator Review Committee 14th~16th March 2025

Contents

Changes

- **Beam optics at IP**

  - Squeeze LER β_x^* from 80 mm to 60 mm to suppress horizontal beam size in LER.

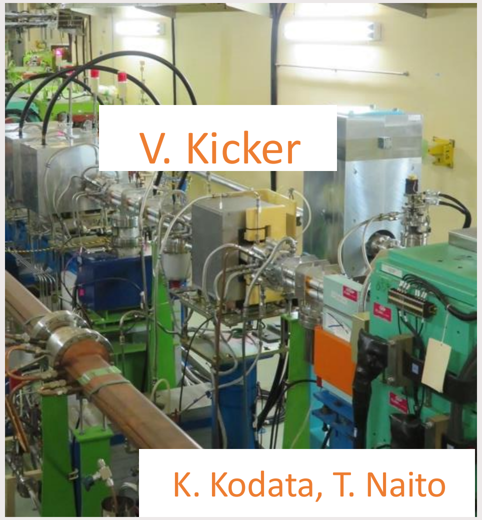
- **Beam optics at Non-linear collimator (D05V1)**

  - Reduce β_x^* at skew sextupoles from 7 m to 3 m to reduce injection background.

- **Beam optics at the LER injection point**

  - Enlarge β_x^* from 100 m to 160 m to suppress the oscillation of the injected beam.

- **Installation of a vertical kicker for the LER beam measurement**



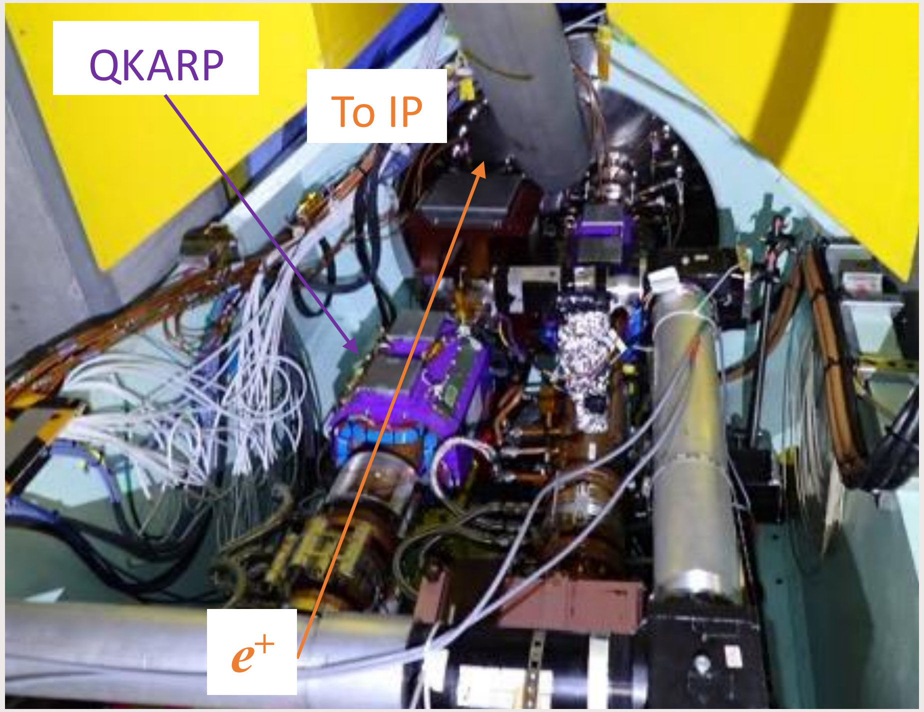
- **Improvement of Continuous Closed orbit correction (CCC)**

  - Constraints on orbit at all sextupole magnets was added to the caluculation.

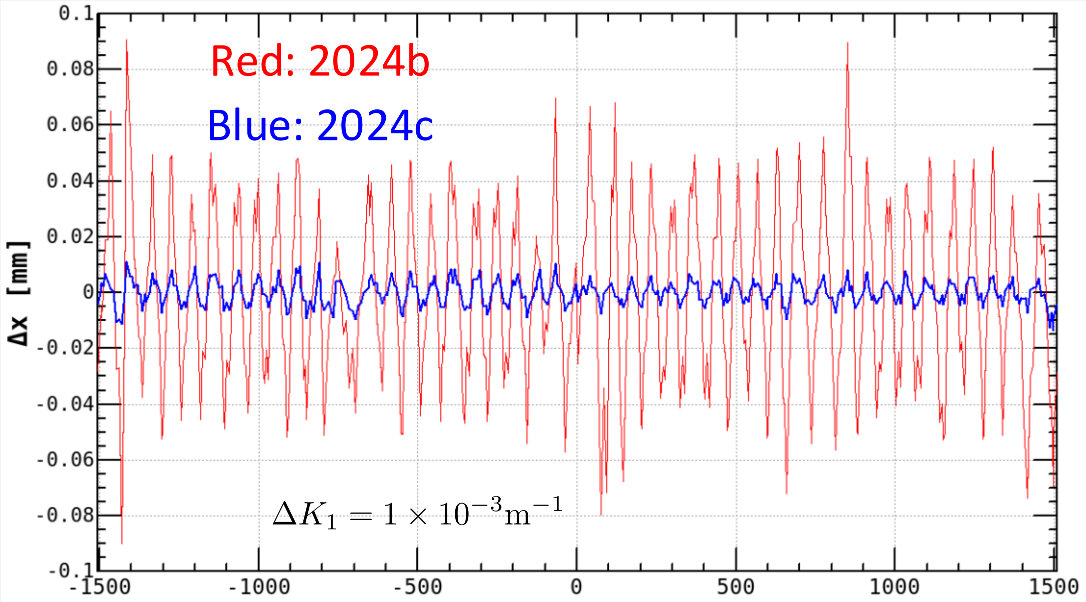
- **Isolation of a BPM from quadrupole magnet in the left side of the LER Y-LCC section**

Changes (Cont'd)

- **Re-alignment of a skew quadrupole magnet near the LER interaction region (IR)**
  - Orbit bump at IR is utilized to adjust the vertex position and luminosity performance.
  - As the results, beam orbit somehow has large offset respect to skew quadrupole magnets near IR.
  - A skew quadrupole magnet (QKARP) was vertically downward by 1.9 mm to align with the beam orbit.
  - Orbit and optics distortions cause by the field change of QKARP was reduced as expected.



Horizontal orbit distortion caused by the field change of QKARP



Large Vertical Emittance in HER

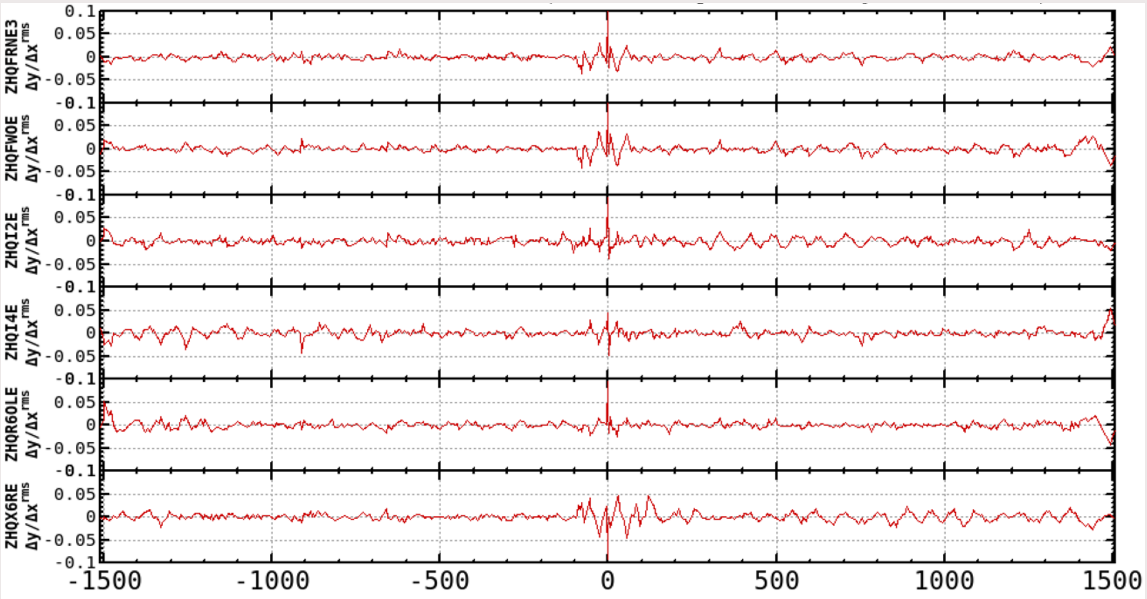
Vertical Emittance in HER

- Vertical emittance after low emittance tuning (LET) is $\boldsymbol{\varepsilon_y = 50 \sim 80}$ **pm**. (cf. $\varepsilon_y = \sim 20$ pm in 2024ab)
- What is unusual is that the rms residual of optics error is similar to that of 2024ab.
- It seems that the problem was started at the 2024c startup, when vacuum scrubbing is performed.

Vertical Leakage Orbit Induced by Horizontal Dipole Kicks

2024ab 03/05 $\beta_y^* = 1$ mm

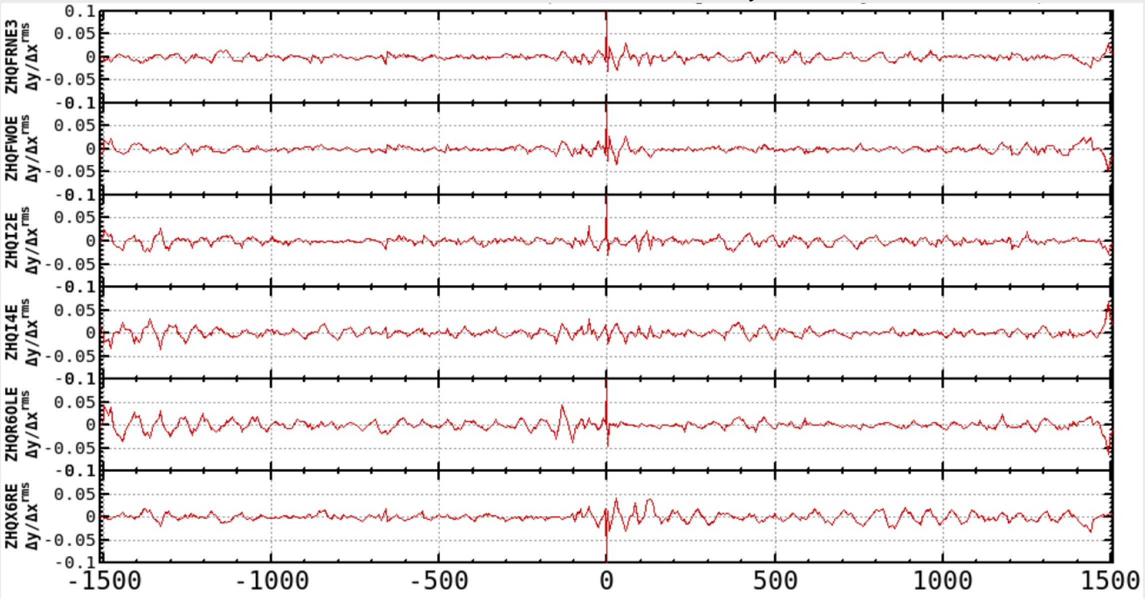
$\Delta y^{\rm rms}/\Delta x^{\rm rms} = 0.01$ $\varepsilon_y = \sim 20$ pm



IP

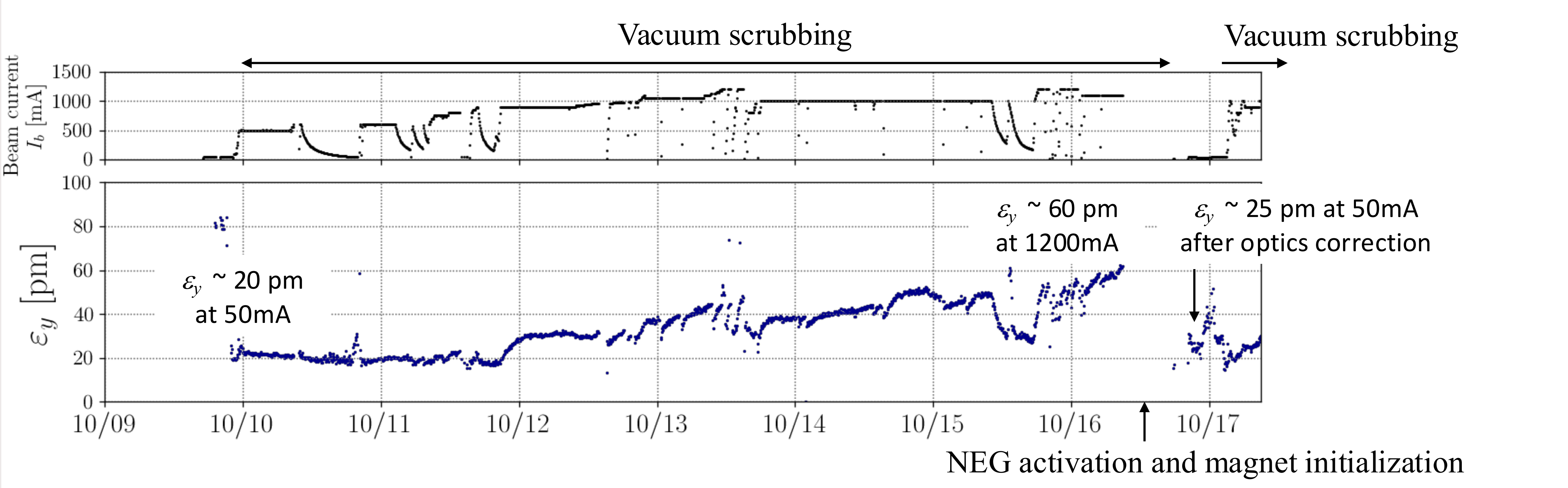
2024c 11/13 $\beta_y^* = 1$ mm

$\Delta y^{\rm rms}/\Delta x^{\rm rms} = 0.01$ $\varepsilon_y = \sim 70$ pm



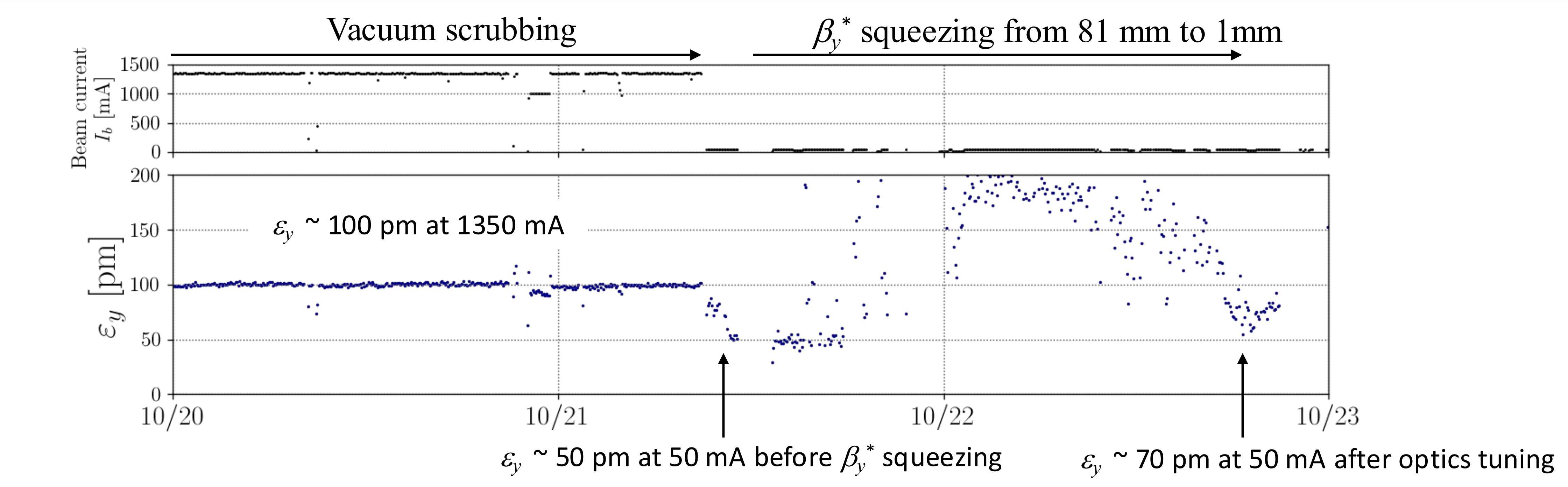
Vertical Emittance during 2024c Startup

- 10/09: The startup with detuned optics (β_y^* = 81 mm). ε_y **~ 20 pm** at 50 mA stored beam current
- 10/09 -> 10/16: Vacuum scrubbing with increasing beam current. ε_y **~ 60 pm** at 1200mA
- 10/16: Temporary operation suspension for NEG activation. The magnet initialization was also performed.
  The optics correction achieved ε_y **~ 25 pm** without any difficulties.
- 10/21: Resume vacuum scrubbing with increasing beam current.



Vertical Emittance during 2024c Startup (Cont'd)

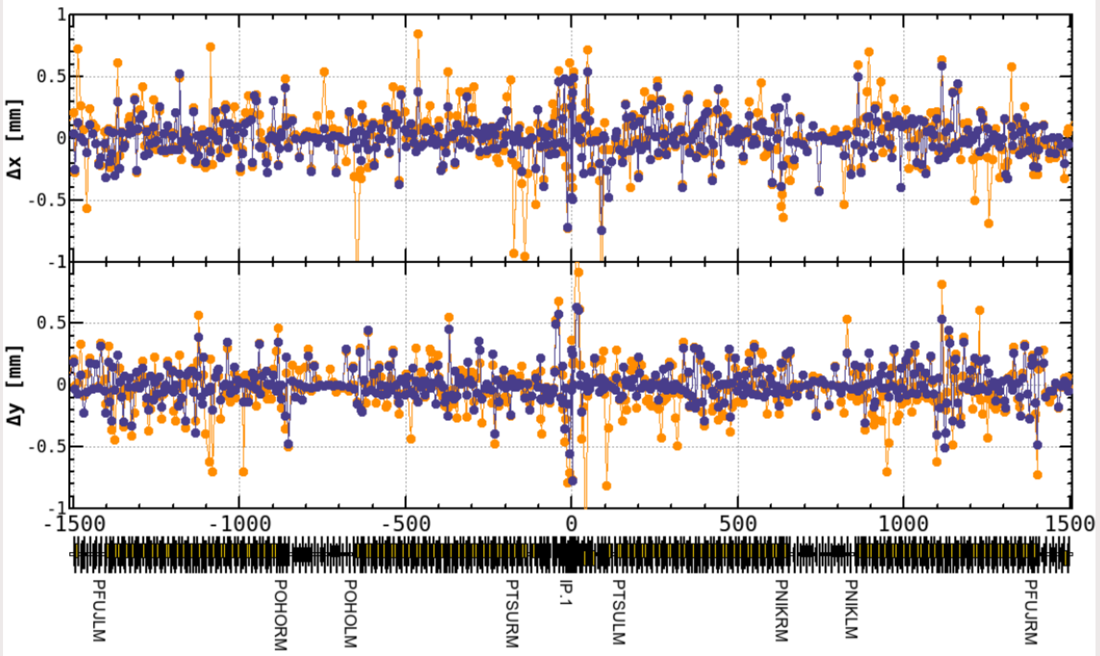
- 10/17 -> 10/21: Vacuum scrubbing with increasing beam current (ε_y **~ 100 pm** at 1350 mA)
- 10/21: β_y^* squeezing (β_y^* = 81 -> 3 -> 2 -> 1 mm)
  ε_y **~ 50 pm** at 50 mA before the β_y^* squeezing (No optics correction was performed at that time)
  ε_y **~ 70 pm** for β_y^* = 1mm optics after optics tuning.
- We tried to reduce the vertical emittance by
  magnet initialization, IP orbit angle tuning, rollback of magnet settings and orbit cleaning.
  However, we never reached ε_y < 50 pm for β_y^* = 1mm optics.

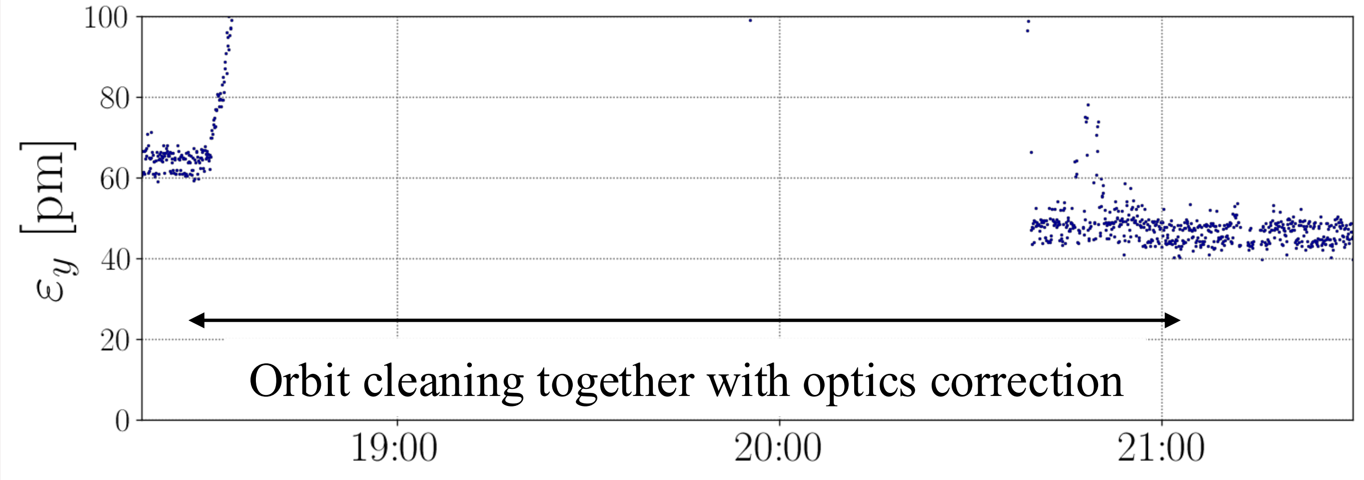


Study on HER Emittance 11/18 ~ 11/20

- Back to the detuned optics and check the emittance after the optics correction.
- We found that the emittance is ε_y **~ 60 pm** even for the detuned optics and we could not recover the ε_y **~ 20 pm**
- To improve the situation, we applied orbit cleaning and make the golden orbit smoother.
- The achieved emittance is ε_y **= 40 ~ 50 pm** and is still larger than the original value ε_y **~20 pm**

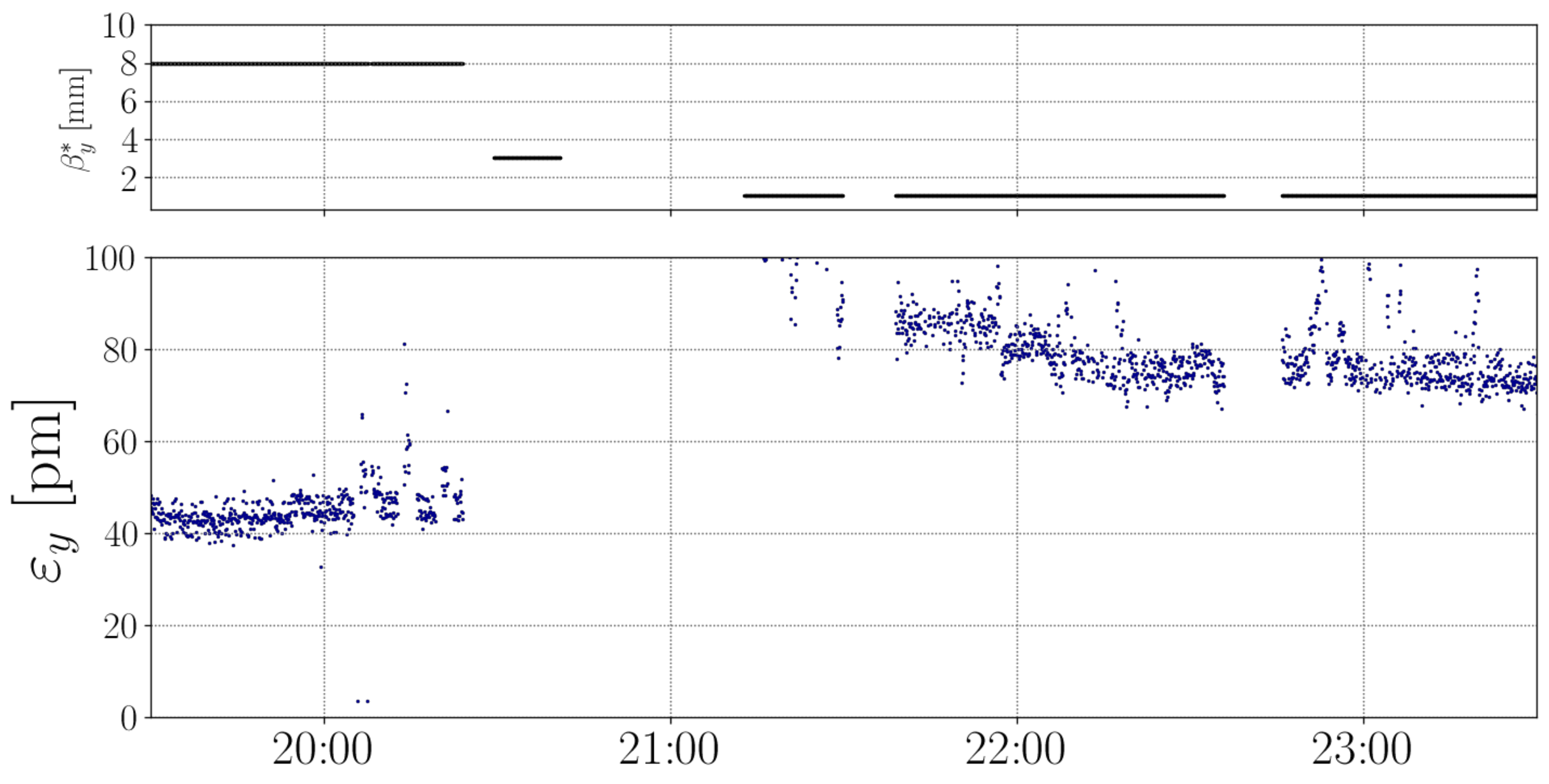
COD Before and After the Orbit Cleaning





Study on HER Emittance 11/18 ~ 11/20

- After the orbit cleaning, we squeezed β_y^* from the detuned optics to β_y^* = 8 mm.
- The emittance for β_y^* = 8mm is ε_y = 40~50 pm after fine optics tuning.
- The emittance is, however, ε_y = 70 ~ 80 pm when we squeeze β_y^* down to 1 mm.

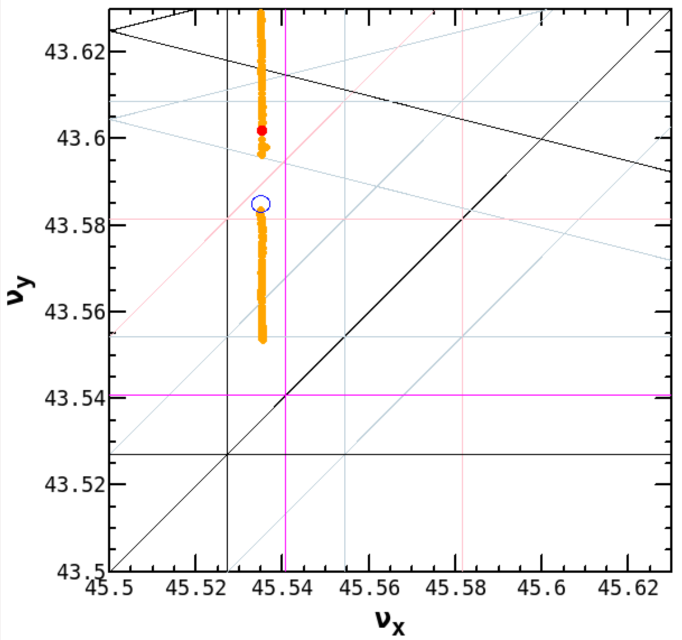


β_y^* and ε_y

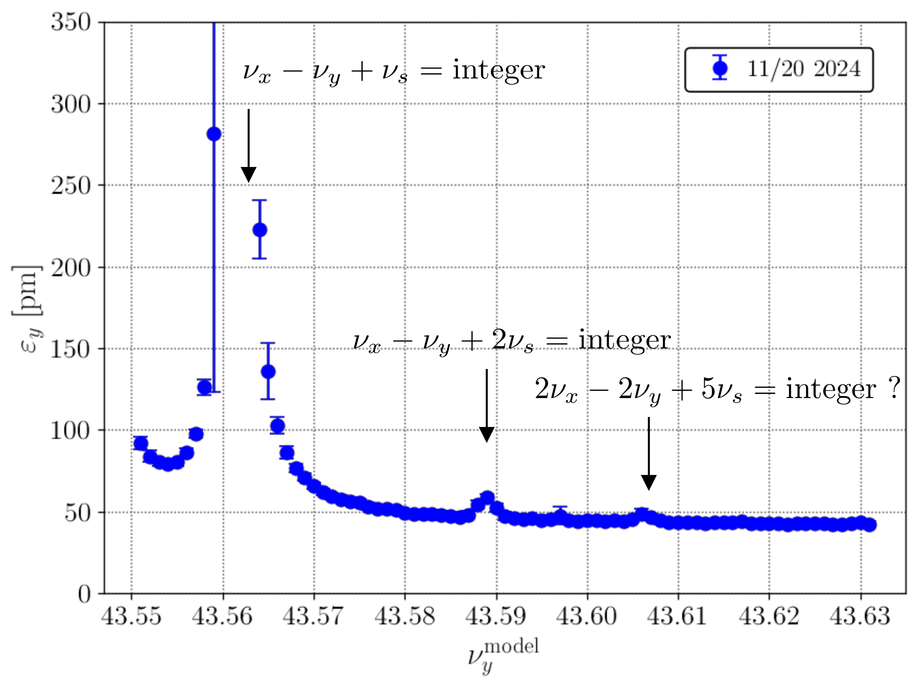
β_y^* = 81 mm	: ε_y = 40 pm
β_y^* = 8 mm	: ε_y = 40~50 pm
β_y^* = 3, 2 mm	: No data
β_y^* = 1 mm	: ε_y = 70~80 pm

Vertical Tune Scan

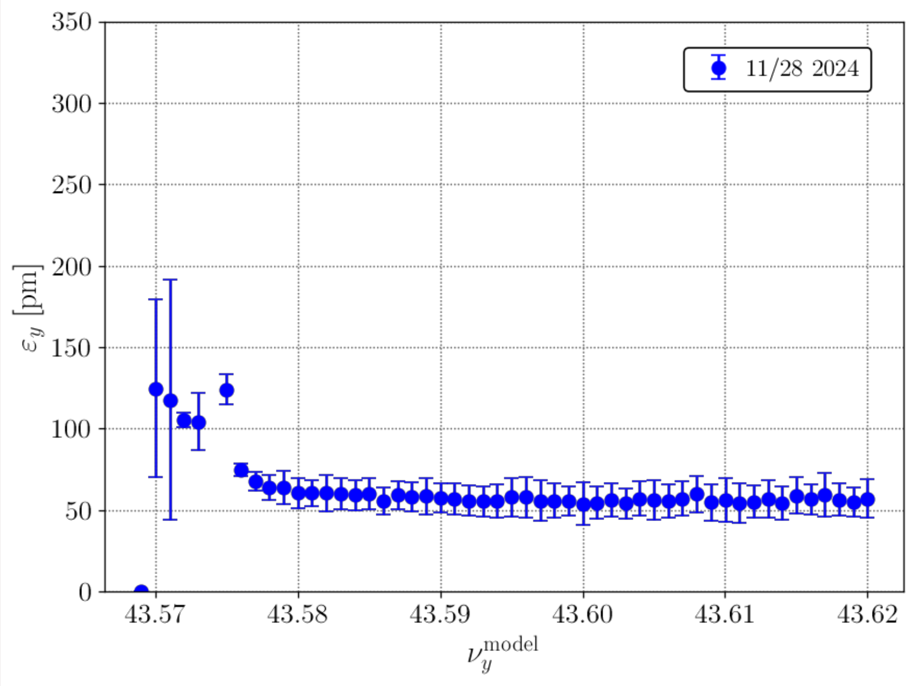
- The emittance is high even the tune is far away from resonances.
- Higher vertical tune slightly improves emittance, but not sufficient.
- Stop bands become weaker in the detuned optics as expected. However the baseline stays high level.



$\beta_y^* = 8$ mm

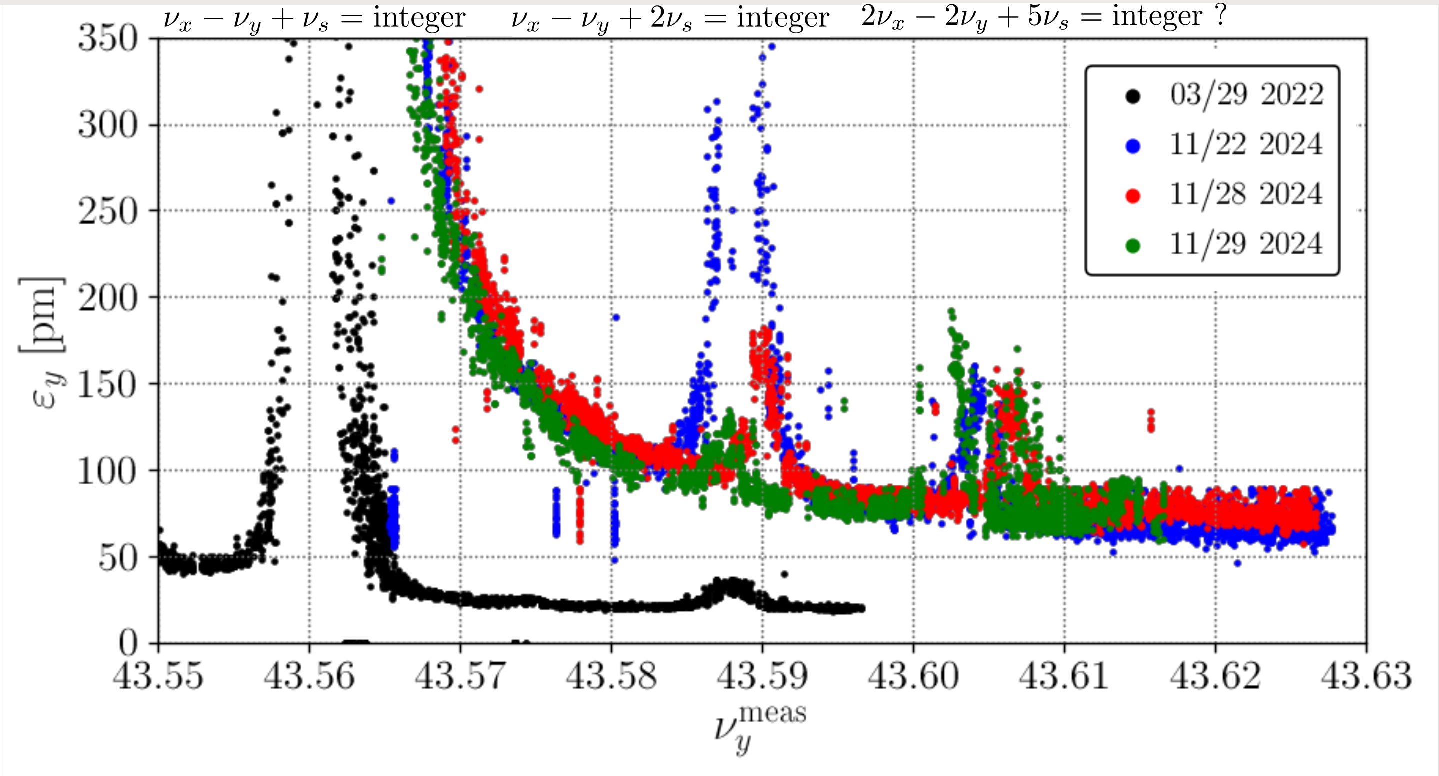


Detuned Optics

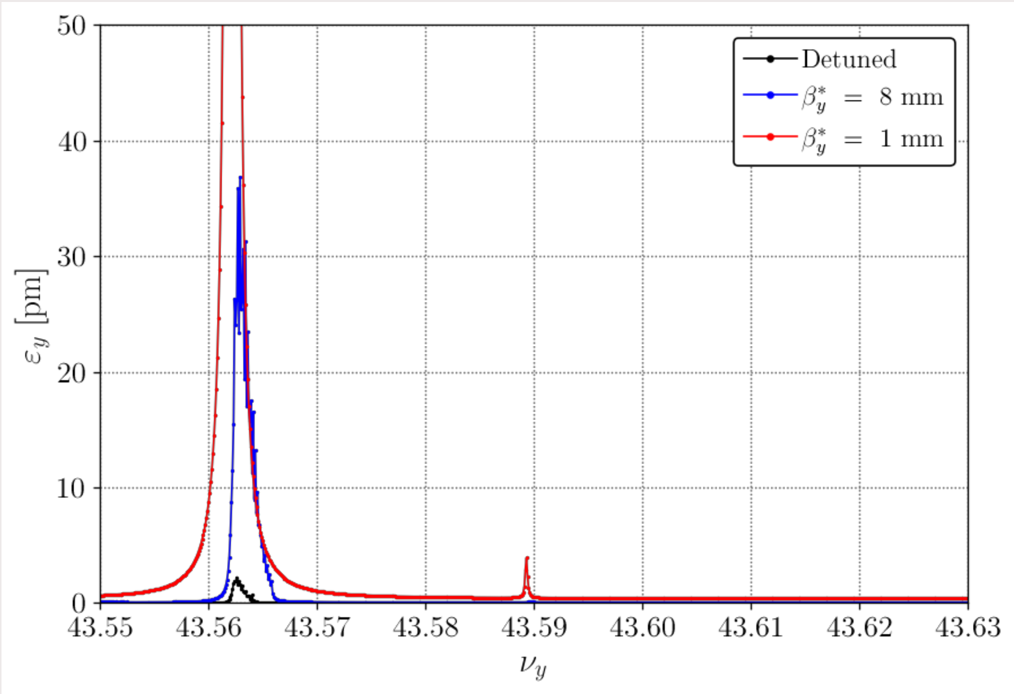


Vertical Tune Scan for $\beta_y^* = 1\ \mathrm{mm}$ Optics

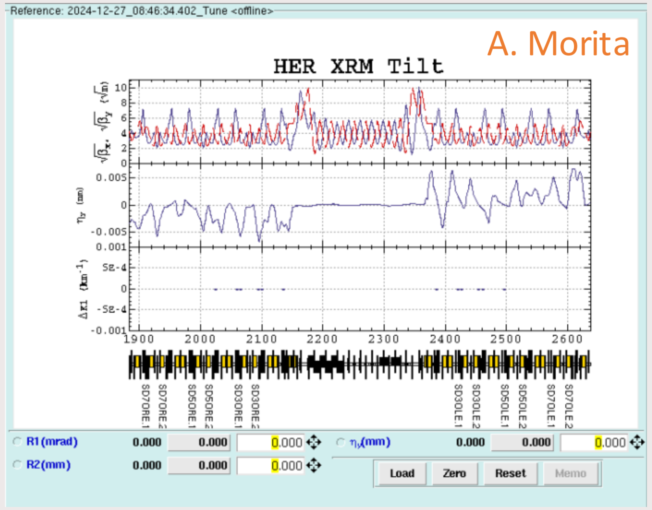
- We have tried several vertical tune scan for β_y^* = 1mm in the 2024c.
- The resonance at $\nu_y \sim 43.605$ is not observed in the simulation with the model lattice.
- Resonance strength seems to depend on the details of the optics correction?



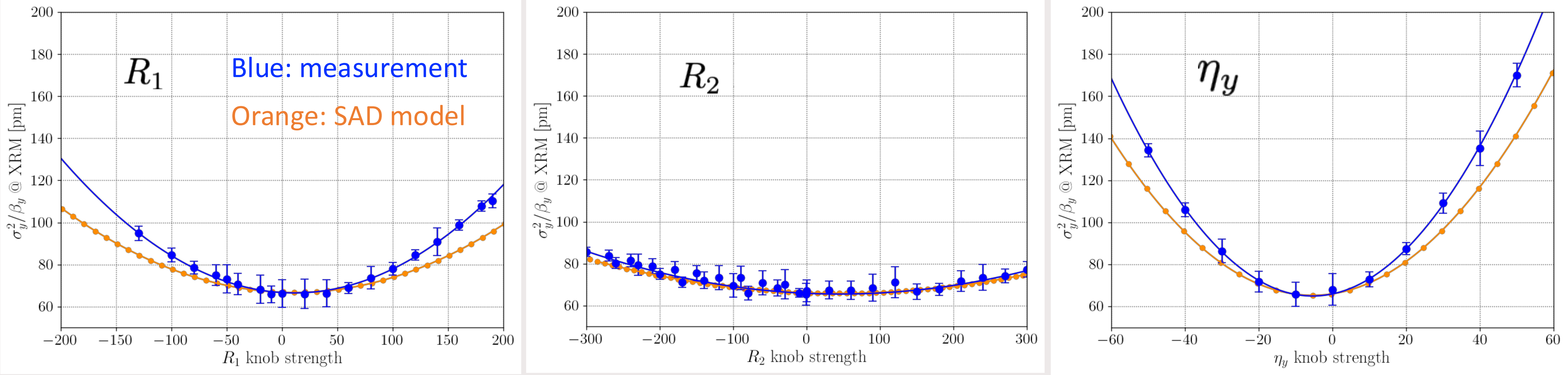
SAD Calculation



Beam Size Scan at X-ray Beam Size Monitor (XRM)

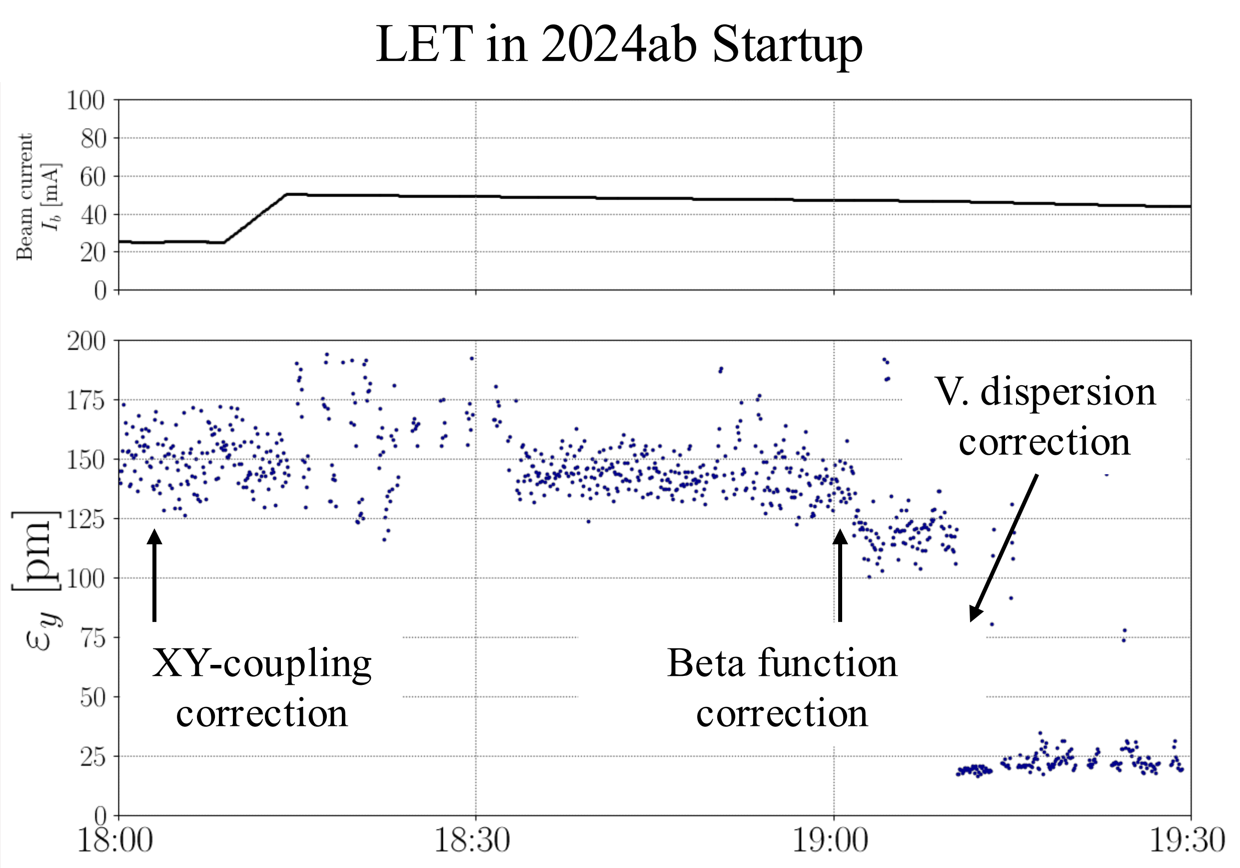


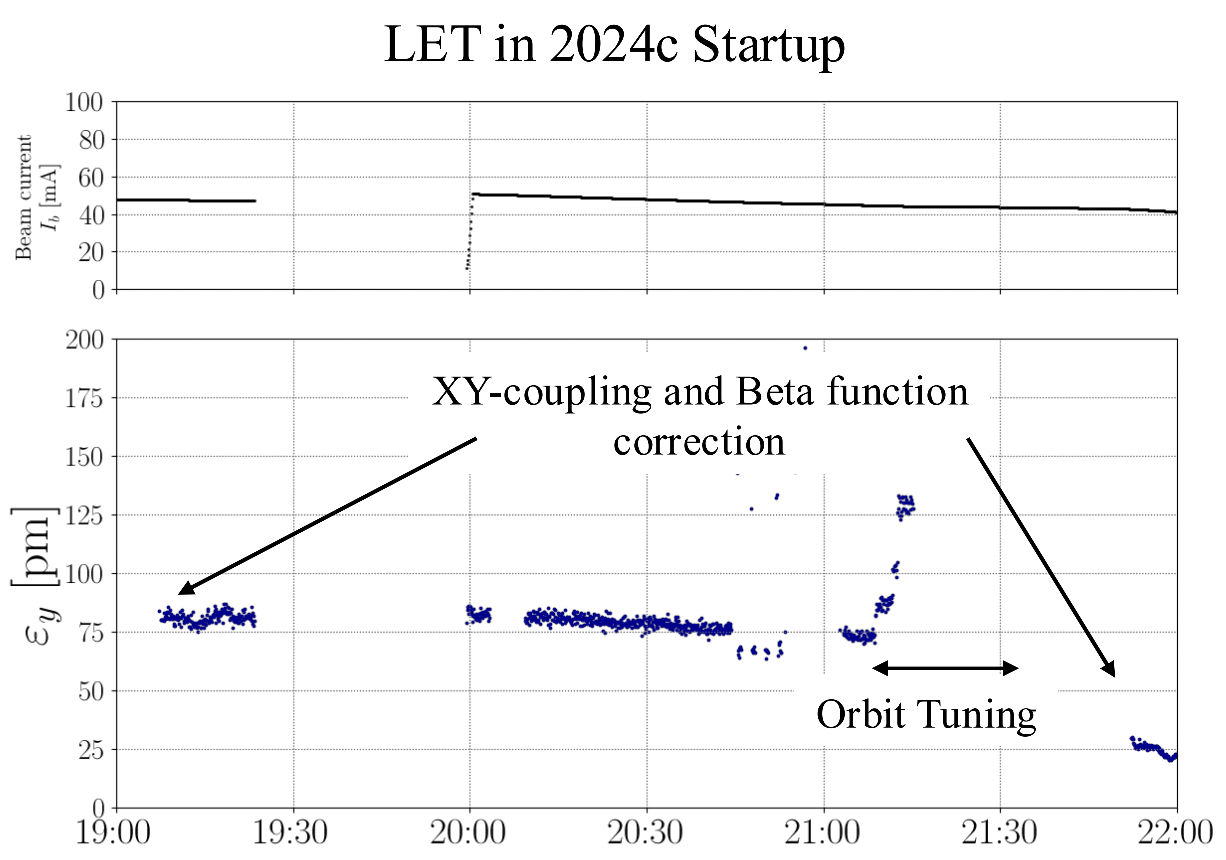
- A possible scenario for the measured large emittance is localized XY-coupling and vertical dispersion at X-ray source point.
- We developed a tuning knob to control these parameters.
- The vertical beam-size scan using the tuning knob were performed.
- The beam size could not be improved drastically by adjusting the tuning knobs.



Our Experience on LET for Detuned Optics

- Based on our experience, low emittance tuning (LET) for detuned optics is straightforward and not difficult.
- Usually, applying only a few corrections easily reduces the vertical emittance.
- Unusually, we never achieve 20 pm in the detuned optics after the 2024c vacuum scrubbing.

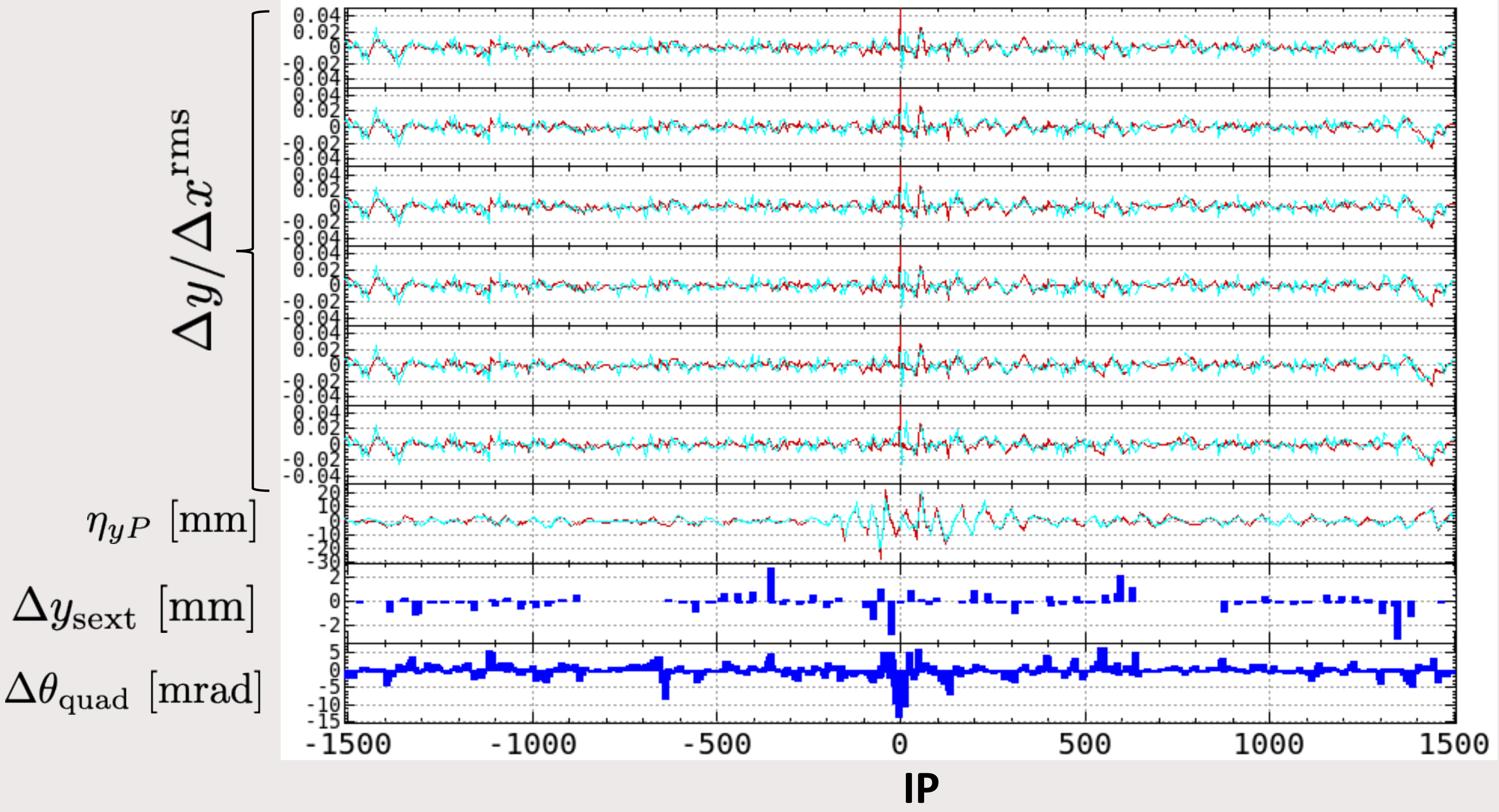




Estimation of Vertical Emittance

- Detuned Optics -

- Try to reproduce the measurement with the vertical offset of sextupoles and the rotation of normal quadrupoles.
- Calculate the emittance using the fitted model lattice.



Red: Measurement

Cyan: Fitted

$\varepsilon_y \sim 1$ pm

- Although the results depends on numerical parameters used in the fitting, it is not easy to reproduce vertical emittance of 50 pm with measured beam optics.

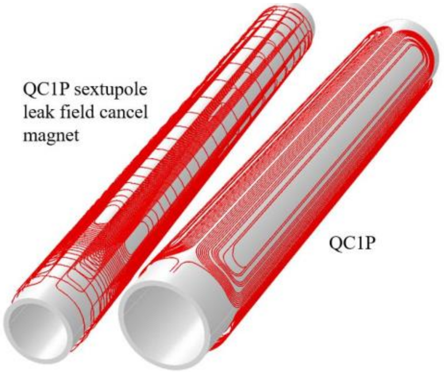
Amplitude Detuning in HER

QCS Error Field and Amplitude Detuning in HER

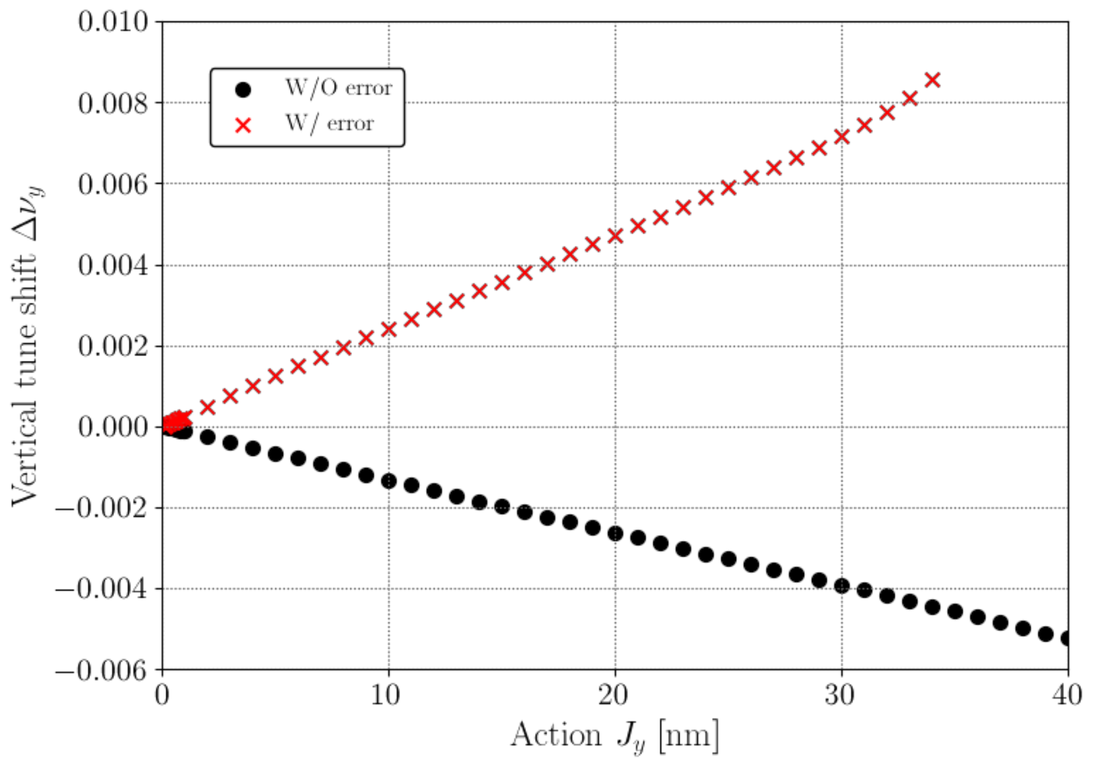
- Cancel coils for leakage field from QC1P in the HER beamline have manufacturing errors.
- It causes additional skew sextupol&octupole fields and affects amplitude detuning.

Table 24: Measured integral leak fields at R_{ref}=10 mm

	QCSL, Tm		QCSR, Tm	
Mag. type	without cancelling	with cancelling	without cancelling	with cancelling
b_3	3.36×10^{-3}	2.32×10^{-5}	-3.53×10^{-3}	1.27×10^{-5}
b_4	-7.58×10^{-4}	-2.83×10^{-6}	8.02×10^{-4}	4.39×10^{-6}
b_5	1.57×10^{-4}	3.66×10^{-6}	-1.67×10^{-4}	-3.73×10^{-6}
b_6	-2.98×10^{-5}	7.8×10^{-7}	3.24×10^{-5}	2.35×10^{-6}
a_3	-2.42×10^{-4}	-3.88×10^{-4}	-2.52×10^{-4}	-4.93×10^{-4}
a_4	-5.88×10^{-5}	-1.16×10^{-4}	4.94×10^{-5}	1.71×10^{-4}
a_5	-1.48×10^{-5}	-1.48×10^{-5}	6.26×10^{-6}	-8.31×10^{-6}
a_6	1.88×10^{-5}	1.48×10^{-5}	-4.31×10^{-6}	-1.09×10^{-6}



Single particle tracking simulation



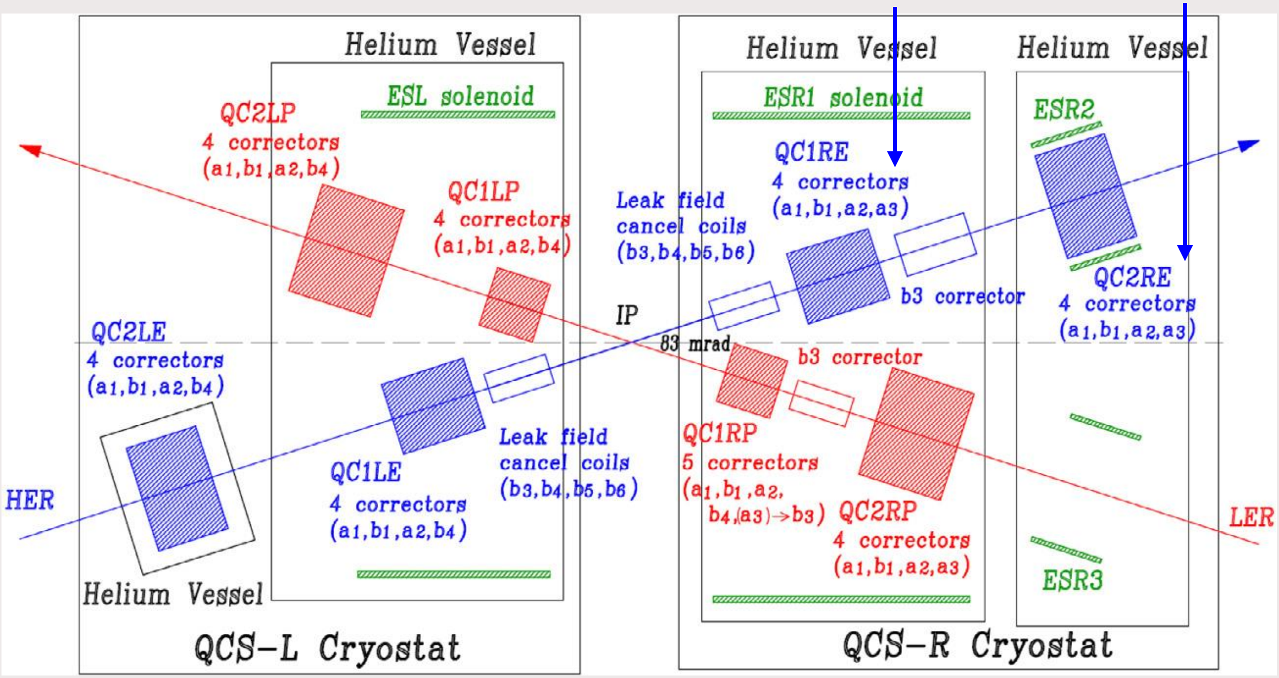
Amplitude Detuning due to Skew Sextupoles

- Skew sextupole causes amplitude detuning in second-order of its field strength.

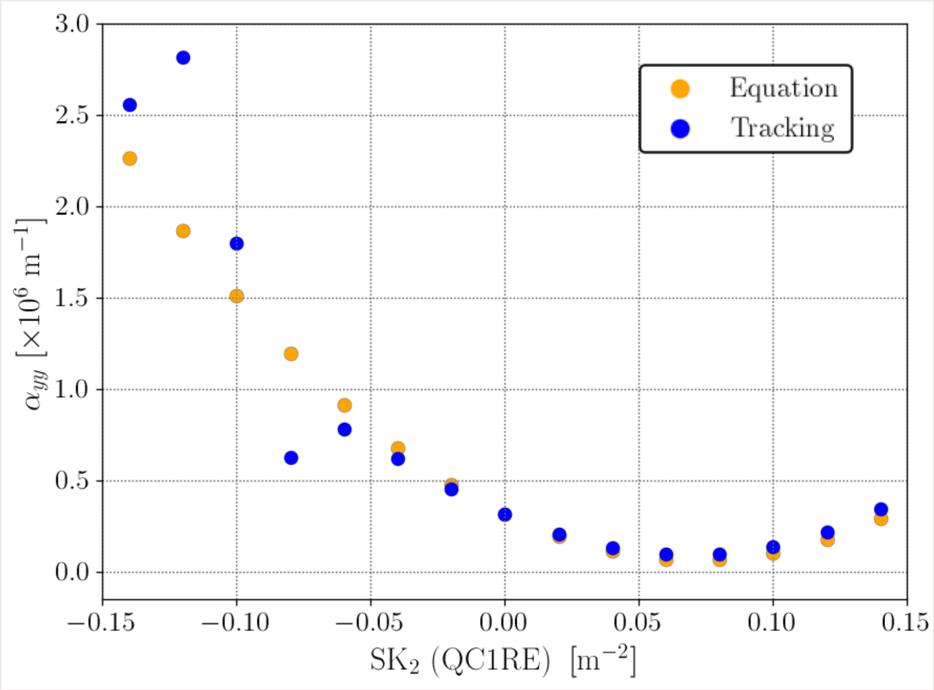
$$\alpha_{yy} = -\frac{1}{64\pi}\sum_i\sum_j \beta_{y_i}^{3/2}\beta_{y_j}^{3/2}(\mathrm{SK2})_i(\mathrm{SK2})_j\left[3\frac{\cos\Phi_y(i,j)}{\sin\pi\nu_y}+\frac{\cos 3\Phi_y(i,j)}{\sin 3\pi\nu_y}\right] \qquad \Phi_x(i,j)=\phi_j-\phi_i-\pi\nu_y$$

- Skew sextupole correctors in IR are expected to utilized as a detuning control knob.

SK2 correctors



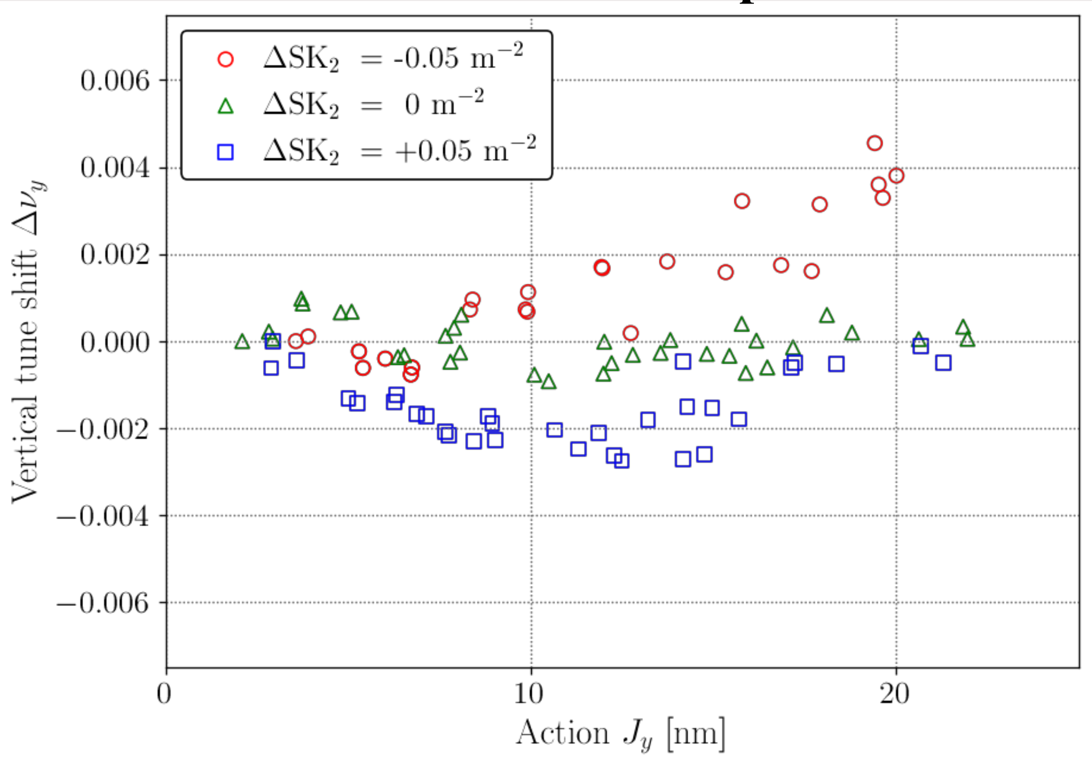
Single particle tracking simulation



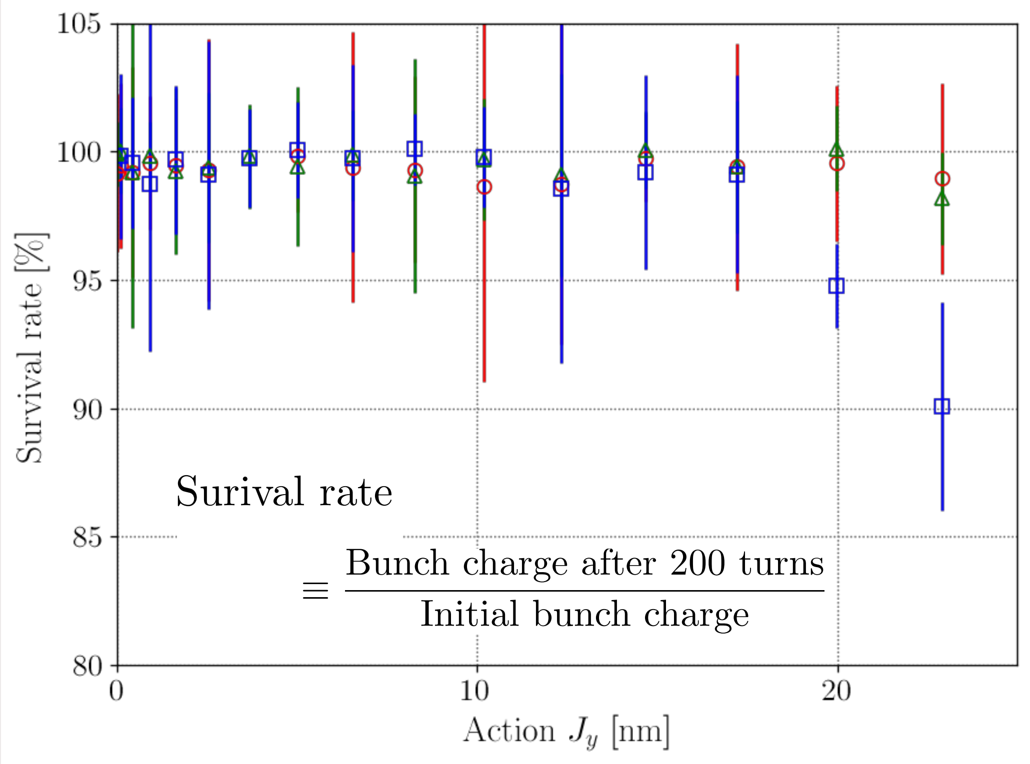
Amplitude Detuning and the QC1RE SK2 Coil

- The amplitude detuning is measured with three different values of the QC1RE SK2 coil.
- It seems that the SK2 coil changes amplitude detuning as expected.
- Dynamic aperture is also affected by the SK2 coil?

Tune Shift with Amplitude



Survival Rate



Summary

- **The large vertical emittance problem in HER was not resolved.**

β_y^*	81 mm (~ 10/21)	81 mm (10/21~)	8 mm	1 mm
ε_y	20 pm	40 ~ 50 pm	40 ~ 50 pm	50~80 pm

  - We achieved $\varepsilon_y \sim 20$ pm for the detuned optics at the early stage of 2024c without any difficulties as usual.
  - However, we can no longer achieve 20 pm for detuned optics.
  - We tried several attempts to revert the magnet settings to those of previous days, but the situation did not improve.
  - Something in the HER beamline, which cannot be identified through beam measurements, has changed or broken during the vacuum scrubbing?

- **Amplitude detuning in HER**
  - Skew sextupole components in IR give rise to the amplitude detuning.
  - A skew sextupole corrector of QC1RE can change the amplitude detuning.

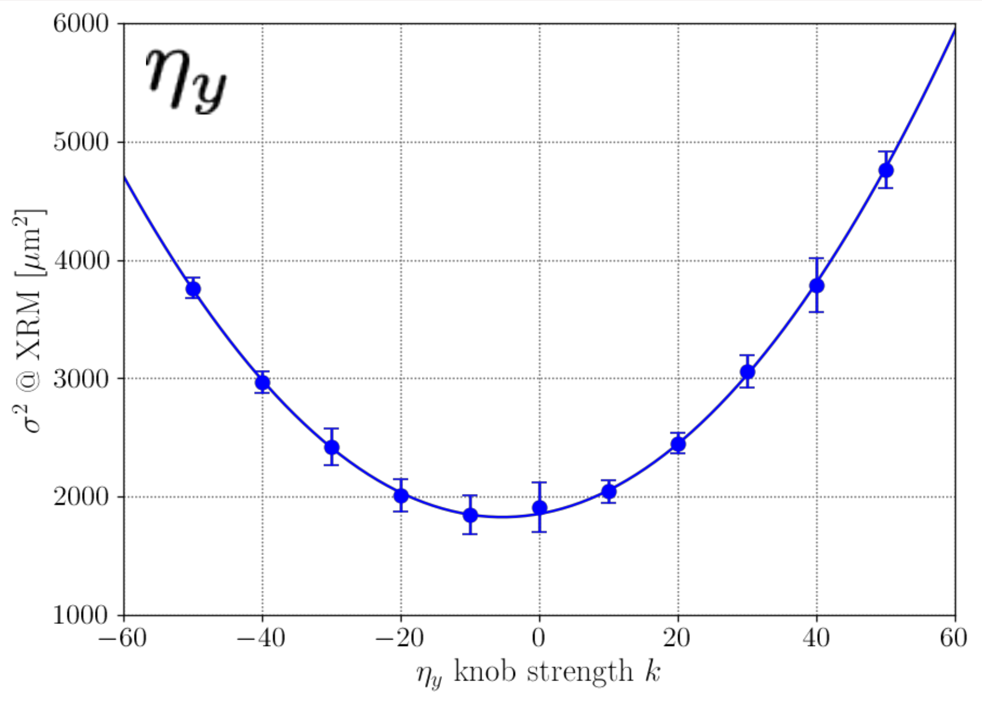
Items for the Future Operation

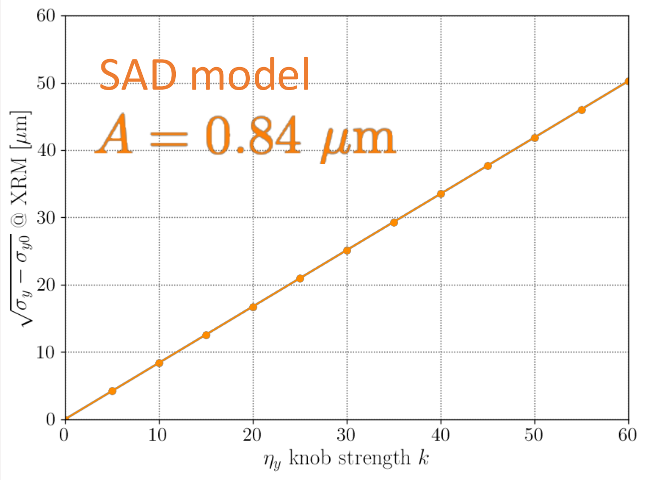
- **Study Items for the HER emittance problem**
  - Perform optics correction for the detuned optics from scratch.
  - Closest tune approach
  - Any other ideas?

- **Model lattice update for more realistic IR model**
  - Magnetic field calculation data, which formed the basis of the current IR model is quite old.
    - Relevant staff at the time was retired or re-assigned, we have to rebuild new framework to update the SAD IR model.
  - QCS group has a more realistic magnetic field calculation model reflecting the results of magnetic field measurements.
  - Revising and organizing the SAD IR model is also helpful for the benchmark with other codes, such as Xsuite.

Thank you for listening

Calibration Factor of Beam Size Measurement





- Measured beam size

$$\sigma^2 = C^2\sigma_0^2 + C^2A^2(k - k_0)^2$$

σ_0 : The minimum beam size

k : Knob strength

k_0 : Knob strength which gives σ_0

C : Calibration factor of beam size measurement

A : Knob response to the beam size (Obtained with the SAD model)

- Fitting Result

$$C^2\sigma_0^2 = 1826 \pm 59\ \mu\mathrm{m}^2$$

$$C^2A^2 = 0.96 \pm 0.04\ \mu\mathrm{m}^2$$

$$k_0 = -5.3 \pm 0.6$$

$$\rightarrow \quad C = 1.17 \pm 0.03$$

$$\sigma_0^2/\beta_y = 47 \pm 4\ \mathrm{pm}$$

$\beta_y = 28$ m

Response To Recommendations MAC 2024

- R10.1: Investigate and correct the IR optics aberrations (QCS correction coils, crab sextupoles, etc.) with the help of optics measurements in different configurations.

  -> Amplitude detuning measurement with changing the QC1RE skew sextupole coil was performed.

- R10.2: Attempt to carry out optics measurements at low current with all collimators open (if possible and safe).

  -> Not performed yet.

- R10.3: Include the error of the QCS correction coils in the base lattice of the HER used for the regular operation.

  -> Not included yet. We understand it is very important. Magnetic field calculation data, which formed the basis of the current IR model is quite old. Relevant staff at the time was retired or re-assigned, we have to rebuild new framework to update the SAD IR model.

- R10.5: Install a vertical kicker for beam dynamics studies in the LER.

  -> Done.